Efficiency and Equity Impacts of Urban Transportation Policies with Equilibrium Sorting

Shanjun Li	Panle Jia Barwick	Andrew Waxman	Jing Wu	Tianli Xia
Cornell & NBER	Cornell & NBER	UT -Austin	Tsinghua	Cornell

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Motivation

- Transportation essential in spatial organization of economic activity in cities
- Choice of transportation policies should be informed by their impacts on urban structure and feedback effects
  - Policy effectiveness; distributional consequences
- Understanding the interactions could be important for policy design to address urban challenges

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Research Questions

- What are the impacts of congestion-reduction policies on residential sorting?
  - Driving restriction, congestion pricing, subway expansion, and combinations
  - Spatial pattern of residential locations; access to jobs and pubic transit
- How does residential sorting in turn alter policy effectiveness?
  - Travel distance and mode; equilibrium congestion
- What are the efficiency and equity impacts of different policies?
  - Channels: housing and travel choices
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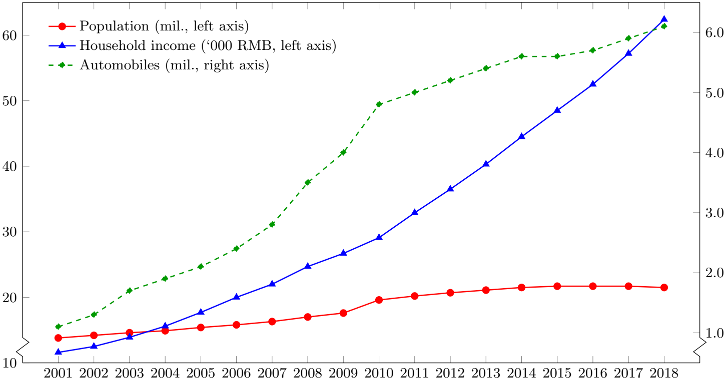
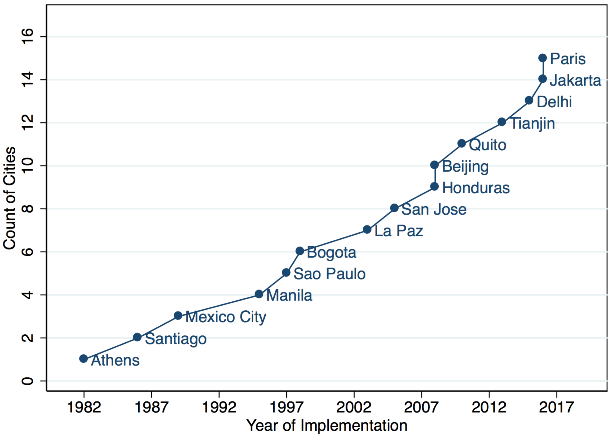
City growth in Beijing from 2001 to 2018



- 55% increase in pop, 500% increase in income and vehicle stock
- One of the most congested and polluted cities in the world
- Average commute: 110 min (80 in NYC, 150 min in Mexico City)

Efforts to combat congestion: driving restriction

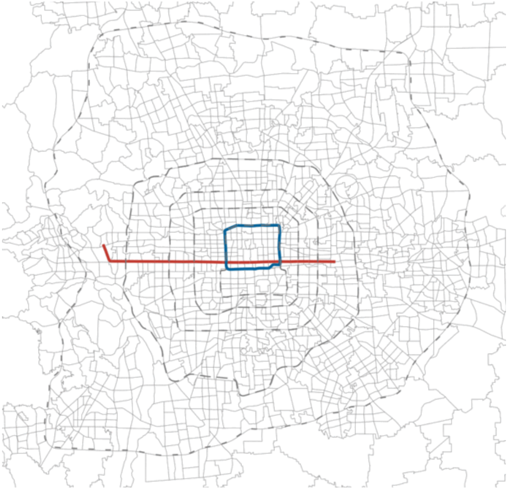
- Driving restriction: from July 2008. Vehicles are restricted 1 day per week, depending on the license plate



Subway expansion in Beijing

- 2 lines (41 stations, 54km) in 2001; 23 lines (370 stations, 699km) in 2019

2001



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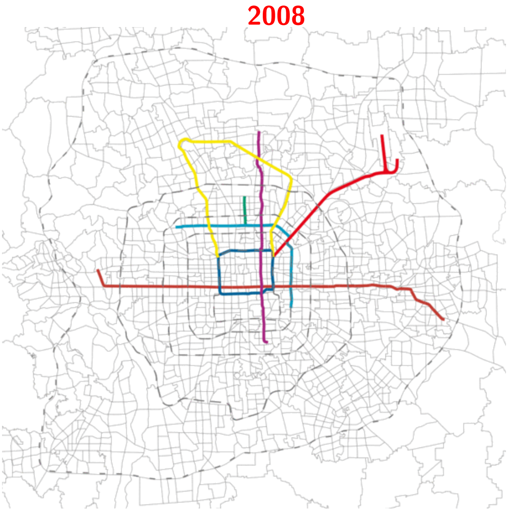

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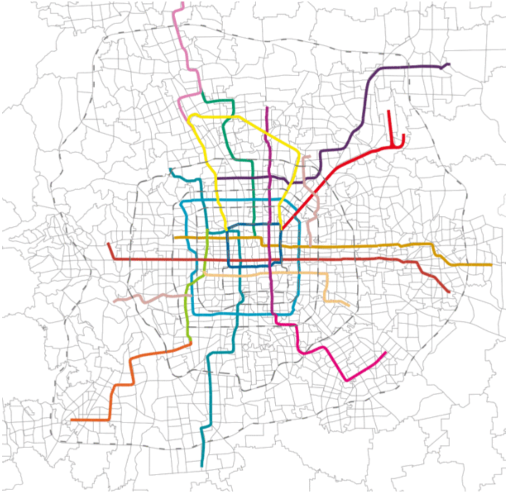

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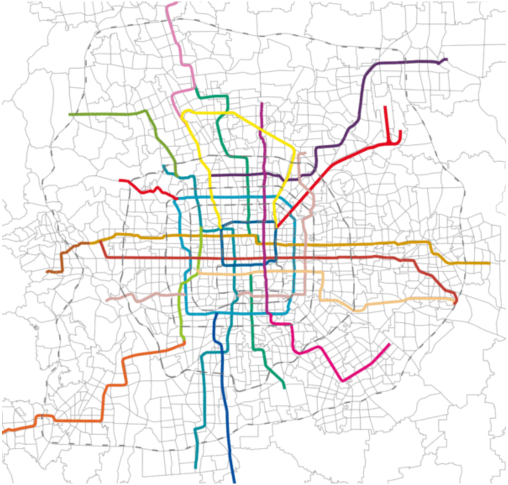


Congestion pricing

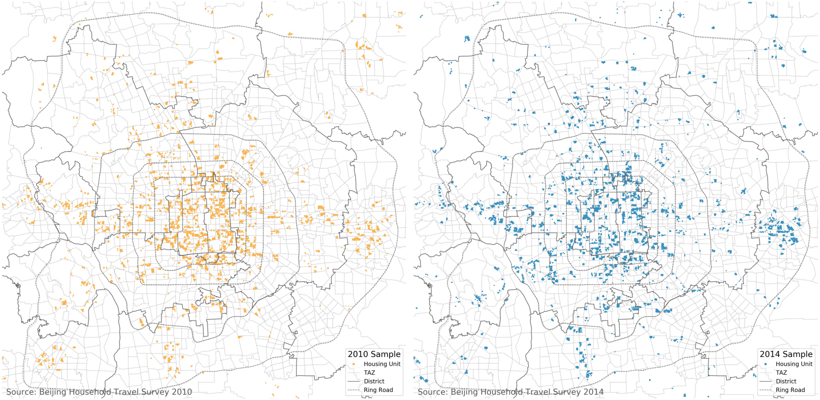
- Root cause of congestion: mispricing of road capacity $\rightarrow$ excess demand
- Vickrey (1963):... in no other areas are pricing practices so irrational, so out of date, and so conducive to waste as in urban transportation
- Congestion Pricing in Practice: technical and political challenges (equity concerns and public acceptance)
  - Singapore (1975), London (2003), Stockholm (2006), Milan (2008), Gothenburg (2013). Slated to start in Manhattan by 2022
  - Dec. 2015, Beijing Municipal Commission of Transport announced plans to introduce congestion charges

2010&2014 Beijing Household Travel Survey

Sum Stat

- Representative survey. 24-hour travel dairy by each individual
- 2010: 46,900 hhs and 253,648 trips. 2014: 40,005 hhs and 205,148 trips

(a) 2010 (b) 2014



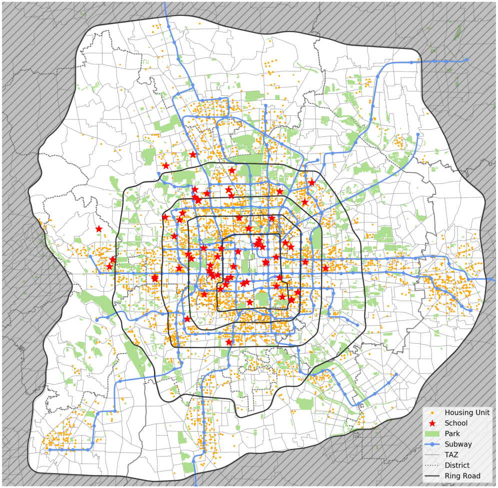
Sample Routes

▸ Mode Shares and Trip Attributes

▸ Recall Bias

Housing data

- Transaction data from government mortgage program 2006-2014
- Household demographics, house attributes, and location of home and work

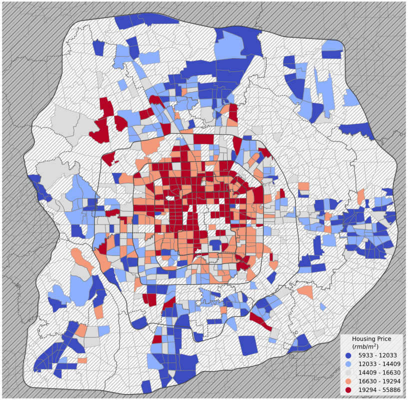


▸ Representativeness: new

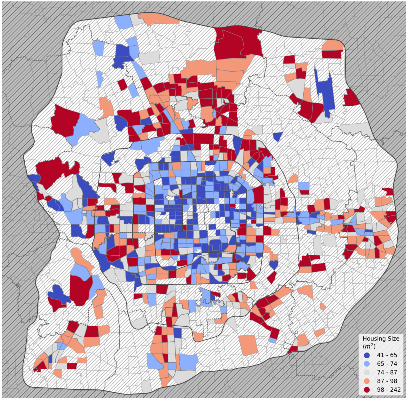
▸ Representativeness: resales

Housing Price and Size by TAZ

(c) Price (per m^2)



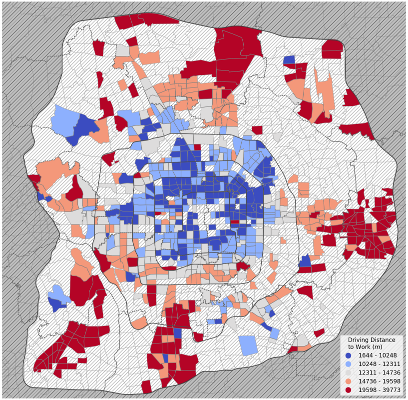
(d) Size



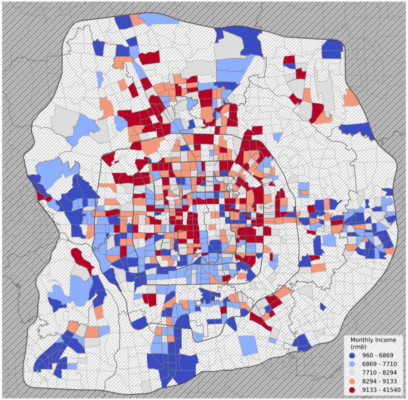
Note: Quintiles based on averages over 2006-2014. Warm colors indicates a higher value.

Work Distance and Monthly Income by TAZ

(e) Work Distance



(f) Household Income



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Sorting Model Overview

- Two-stage nested model on housing and travel choices:
  - Outer nest (housing): conditional on job location, choose housing based on preference for attributes, amenities, commuting convenience to work
  - Inner nest (travel mode): conditional on job and housing locations, choose travel mode based on modes available and traffic congestion
  - Innovations: endogenous congestion; work-commute as housing attribute
- Model scope: (a) work commute, (b) housing supply calibrated, (c) job locations fixed ▸ Job Turnover

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Housing choice

$$\max_{\{j \in J_i\}} U_{ij} = \alpha_i p_j + \mathbf{x}_j \beta_i + \gamma_i EV_{ij} + \xi_j + \epsilon_{ij},$$

- i: household, j: housing choice
- p_j is the price of housing j
- $\mathbf{x}_j$ is a vector of housing attributes
- EV_{ij} is expected utility from the best commuting mode
- ξ_j is a vector of unobserved attributes
- ϵ_{ij} is Type I Extreme Value error

$$\alpha_i = \bar{\alpha} + \mathbf{z}_i \alpha$$

$$\beta_{ik} = \bar{\beta}_k + \mathbf{z}_i \beta_k$$

- $\mathbf{z}_i$ household demographics (observed and unobserved)

Travel mode choice

$$\max_{m \in M_i} u_{ijm} = \theta_{im} + \gamma_1 time_{ijm} + \gamma_2 cost_{ijm}/y_i + \mathbf{z}_i \eta_m + \varepsilon_{ijm},$$

- i: household; j: housing choice; m: travel mode
- θ_{im}: random coefficients on modes
- $time_{ijm}$ is commute time of mode m
- $cost_{ijm}$ is out-of-pocket cost of mode m
- y_i is the income of household i

- The value of time is given by: $\frac{\gamma_1}{\gamma_2} \cdot y_i$

$$EV_{ij} = \log\left(\sum_{m \in M_i} \exp\left[\theta_{im} + \gamma_1 time_{ijm} + \gamma_2 cost_{ijm}/y_i + \mathbf{z}_i \eta_m\right]\right)$$

Sorting Equilibrium

- A sorting equilibrium is defined as a set of housing choice probabilities $\{P^*_{ij}\}$, the vector of housing prices $\mathbf{p}^*$, a set of travel choice probabilities $\{R^*_{ijm}\}$, and traffic speed v^* such that:
  - The housing market clears and;
  - Traffic speed $v^* = \mathcal{C}$(car density) is consistent with individual travel choices

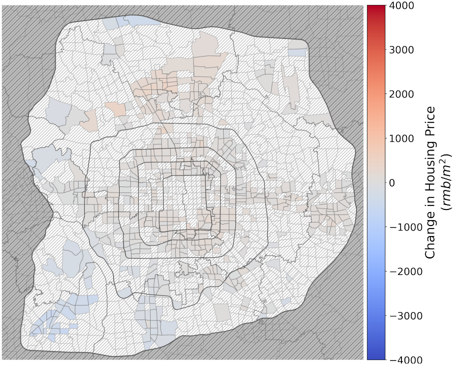
    ▸ Speed function
- A sorting equilibrium exists and is unique under reasonable assumptions on model premises (such as continuous distribution of the error terms)
  - The negative spillover due to traffic congestion leads to uniqueness

Counterfactual Simulations

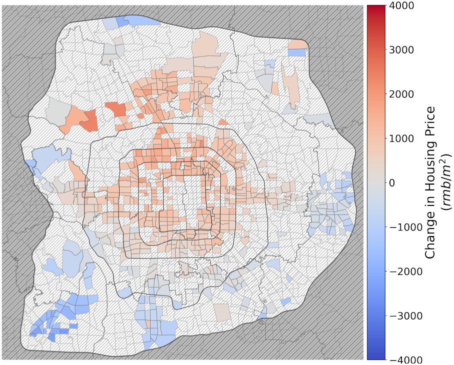
- Consider six scenarios:
  1. 2008 subway network
  2. 2008 subway network + driving restriction
  3. 2008 subway network + congestion pricing
  4. 2014 subway network
  5. 2014 subway network + driving restriction
  6. 2014 subway network + congestion pricing
- Simulation Approach: fixed point iteration
  - Inner Loop: Conditional on congestion level, choose travel modes in response to policy. Construct convenience measure and solve for housing prices that clear housing market.
    - Solve for housing equilibrium.
  - Outer Loop: Given new housing and driving choices, update congestion level
    - Solve for congestion equilibrium
  - Iterate over two loops until fixed points of housing prices & congestion level are found

Changes in housing price relative to baseline (2008 subway)

(g) Driving restriction



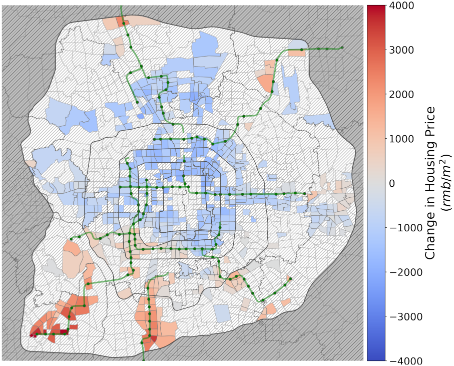
(h) Congestion pricing



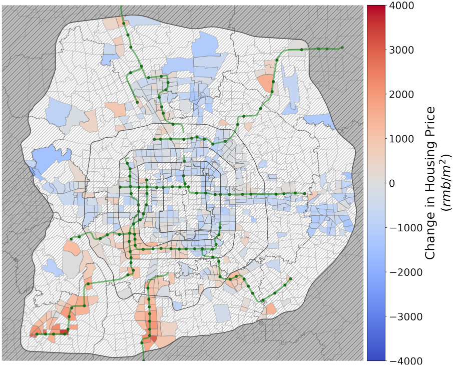
Price gradient
Price gradients w/ 2008 network
Price gradient w/ 2014

Changes in housing price relative to baseline (2008 subway)

(i) Subway Expansion



(j) Subway + Pricing



Simulations: 2008 Network with Sorting

▸ Without Sorting

	(1) No Policy Baseline levels		(2) Driving restriction Δs from (1)		(3) Congestion pricing Δs from (1)	
Income group	High	Low	High	Low	High	Low
Travel mode shares (%)						
Drive	44.98	25.57	-7.79	-3.51	-3.92	-5.17
Subway	7.61	9.49	1.35	0.42	0.37	0.70
Bus	5.06	9.83	0.43	-0.05	0.53	0.96
Bike	22.50	34.02	0.80	0.80	0.59	1.18
Taxi	3.23	1.78	2.82	1.49	1.25	1.13
Walk	16.63	19.33	2.39	0.84	1.18	1.20
Driving speed (km/h)	23.37		4.17		4.17	

- Simulated travel model shares (%) by high- and low- income groups
- Driving restriction: disproportionately more to taxi, not bike and walk
- Congestion pricing (¥1.43/km) set to achieve same reduction as DR
- Congestion pricing: poor reduce driving disproportionately more

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Housing market outcomes						
Distance to work (km)	19.45	18.88	-0.04	0.03	-0.56	-0.28
Welfare per household (1000 ¥)						
Consumer surplus			-181.0	-47.4	-152.1	-148.9
Toll revenue					214.5	214.5
Net welfare			-181.0	-47.4	62.4	65.6

- DR: income-stratified structure. CP: reduce wasteful commuting for all
- DR progressive while CP regressive
- CP improves welfare but revenue recycle needed address equity

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Simulations: 2014 Subway Network

	Subway Expansion Δs from baseline		Expansion + Restriction Δs from baseline		Expansion + Pricing Δs from baseline	
Income groups	High	Low	High	Low	High	Low
Travel mode shares (%)						
Drive	-1.17	-1.36	-8.80	-4.67	-5.21	-6.39
Subway	3.02	4.30	4.81	4.87	3.62	5.48
......						
Driving speed (km/h)	0.95		4.89		5.07	
Housing market outcomes						
Distance to work (km)	0.31	0.32	0.37	0.30	-0.35	0.10
Welfare per household (1000 ¥)						
Consumer surplus	100.9	99.4	-77.3	52.6	-56.8	-41.6
Subway cost	95.3	95.3	95.3	95.3	95.3	95.3
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Net welfare	5.6	4.1	-172.6	-42.7	49.3	64.5

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The Role of Sorting

	Congestion pricing	Subway Expansion
Δ in Speed (km/h) from baseline		
Without sorting	3.98	1.23
With sorting	4.17	0.95
With sorting & supply adjustment	4.38	0.64
Welfare per household (1000 ¥)		
Without sorting	58.2	6.2
With sorting	64.0	4.9
With sorting & Supply adjustment	69.3	3.5

- Strengthens congestion pricing but weakens subway expansion, in terms of both congestion reduction and welfare

The Role of Sorting

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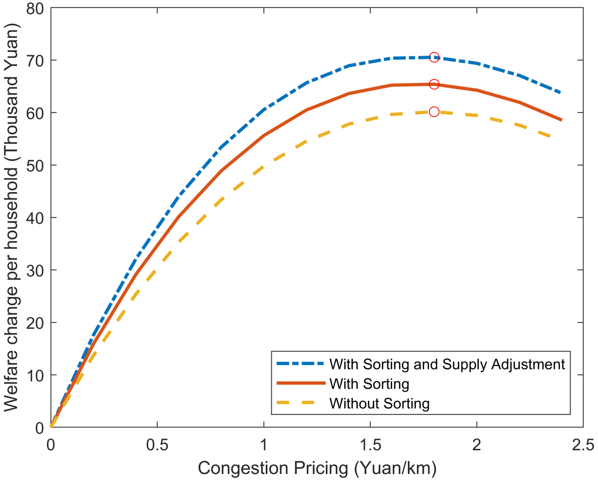
With sorting	4.17	0.95
With sorting & supply adjustment	4.38	0.64
Welfare per household (1000 ¥)		
Without sorting	58.2	6.2
With sorting	64.0	4.9
With sorting & Supply adjustment	69.3	3.5

- Strengthens congestion pricing but weakens subway expansion, in terms of both congestion reduction and welfare

Optimal Congestion Pricing



- Sorting increases welfare by 20% with optimal congestion pricing

Conclusion

- Developed a unified sorting framework with endogenous congestion to compare polices in congestion relief, residential location, and welfare
- Policy impact on residential sorting:
  - Driving restriction intensifies income-stratified urban structure where high-income households live closer to subway and jobs
  - Congestion pricing leads both income groups move closer to jobs, and hence shorter commuter. Subway expansion does the opposite
- Welfare Comparison:
  - Driving restriction reduces welfare but hurt poor less. Congestion pricing improves welfare but revenue recycle needed to address distributional concerns
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THANKS!

SL2448@cornell.edu

Spatial Equilibrium

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- Endogenous congestion and driving commute cost:

$$
\begin{aligned}
w_{d,C}(x) &= \int_0^x t_{d,C}(s)ds \\
t_{d,C}(x) &= \nu_d * \mathcal{C}\left(n_C(x)\right) \\
n_C(x) &= \sum_d \int_x^{\bar{x}} \mathbf{1}\{m = C\}_d(x)ds
\end{aligned}
$$

- A spatial equilibrium is characterized by a bid rent curve $p(x)$: the WTP (per ft^2) while maintaining utility $\bar{u}$.

$$
p^*_{d,m}(x) = \max_{\{c_{d,m}, q_{d,m}\}} \left\{ \frac{y_d - c_{d,m} - \theta_m - w_{d,m}(x)}{q_{d,m}(x)} | u_{d,m} = \bar{u}_d \right\}.
$$

1. All households are housed within the city,
2. At the urban boundary, $\bar{x}$, rent equates agricultural rent $p^*\left(\bar{x}\right) = p_a$,
3. Given identical preferences, all households with same income attain same utility

Summary statistics (2010 Household Travel Survey)

Variable	N	Mean	SD	Min	Max
Household size	46900	2.47	0.98	1.00	5.00
Income (RMB '000)	46886	64.81	33.03	50.00	400.00
# of workers	46900	1.18	0.92	0.00	4.00
House size (m^2)	46868	75.35	43.27	5.00	500.00
House owner (=1)	46900	0.69	0.46	0.00	1.00
Having a car (=1)	46900	0.29	0.45	0.00	1.00
# of cars	46900	0.31	0.51	0.00	4.00
# of bikes	46871	0.96	0.93	0.00	5.00
# of ebikes	46789	0.15	0.40	0.00	4.00
# of motorcycles	46748	0.03	0.18	0.00	3.00
Housing type	46900	1.79	3.23	1.00	96.00
Nature of housing	46900	2.26	1.15	1.00	4.00

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Summary statistics (2014 Household Travel Survey)

Variable	N	Mean	SD	Min	Max
Household size	40005	2.53	1.01	1.00	5.00
Income (RMB '000)	40005	85.39	49.68	50.00	400.00
# of workers	40005	1.18	0.93	0.00	4.00
House size (m^2)	40005	91.08	66.82	5.00	948.00
House owner (=1)	40005	0.61	0.49	0.00	1.00
Having a car (=1)	40005	0.42	0.49	0.00	1.00
# of cars	40005	0.49	0.62	0.00	4.00
# of bikes	40005	0.88	0.86	0.00	5.00
# of ebikes	40005	0.31	0.56	0.00	5.00
# of motorcycles	40005	0.03	0.18	0.00	5.00

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Mode-specific Travel Time

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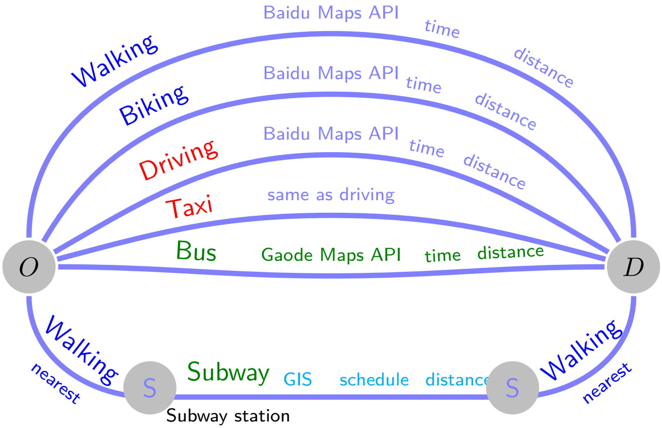

Note: car, bus and taxi trips are based on the real starting time and the day of the week. Travel time adjusted based on contemporary driving speed in 2010 and 2014.

Mode-specific out-of-pocket cost

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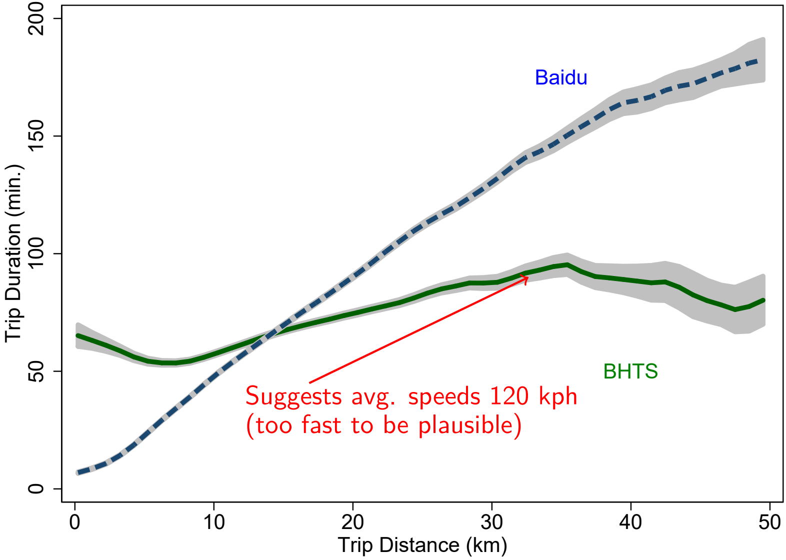
1. **Driving**: 0.64 yuan/km for 2010 and 0.71 yuan/km for 2014
2. **Subway**: for each trip, 2 yuan for taking subway (and based on card type)
3. **Bus**: for each transfer, 0.2 yuan for students, 0 for elderly people, 0.4 yuan for people with public transportation cards, and 1 yuan for people without public transportation cards.
4. **Walking**: zero cost
5. **Biking**: zero cost for own bike and rental bike is free for the first hour and then 1 yuan per hour. Max 10 Yuan for 24 hours.
6. **Taxi**: In 2010, 10 Yuans for the first 3km and then 2 Yuans per km and 1 Yuan gas fee. In 2014, 13 Yuans for the first 3km and then 2.3 Yuans per km plus 1Yuan as gasoline fee.

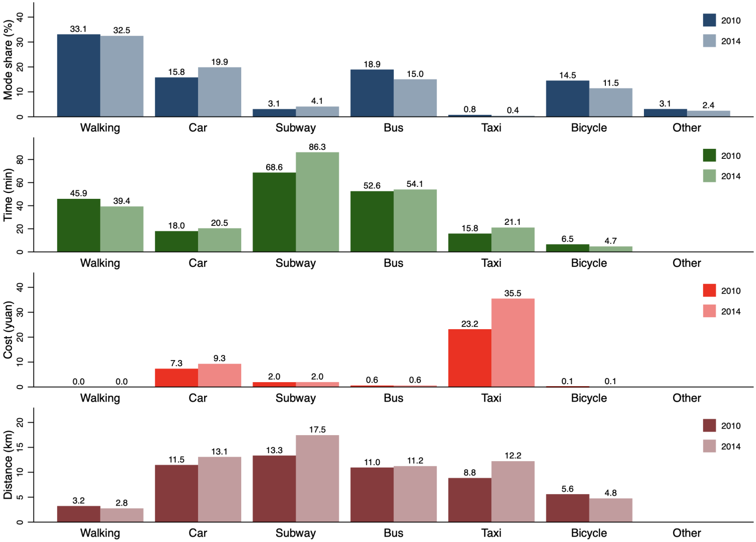
Potential Recall Bias: Subway Trips

Back



Mode Share & Trip Attributes (2010 & 2014)

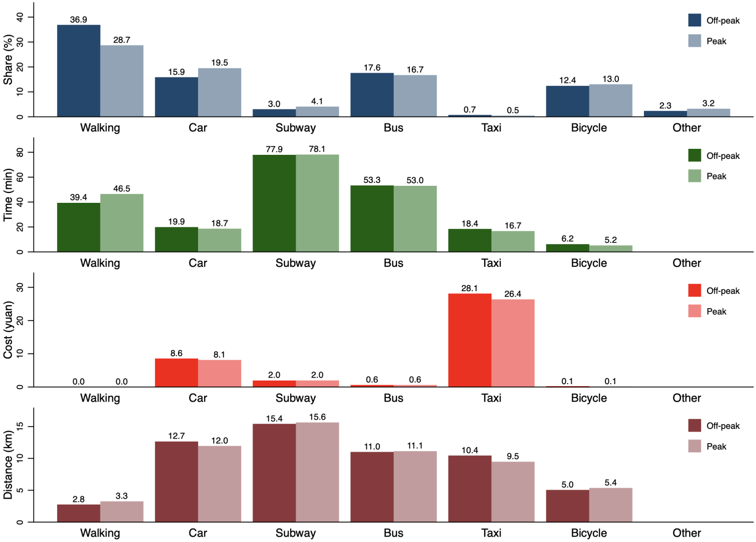
Back



Note: Time and cost estimated based on geocoding

Peak vs. off-peak

Mode Share and Trip Attributes (Off-peak vs Peak)



Note: Peak hours: 7-10am, 5-7pm.Time and cost estimated based on geocoding

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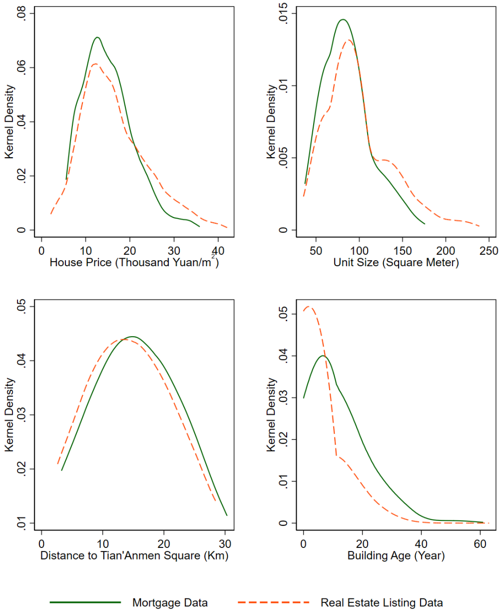
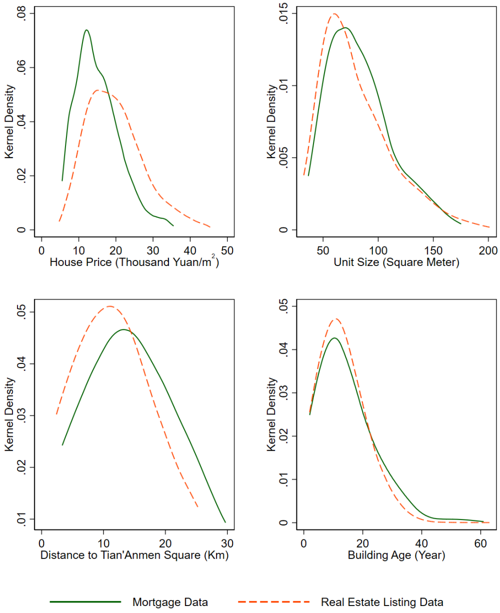
Sample Representativeness: New

Back



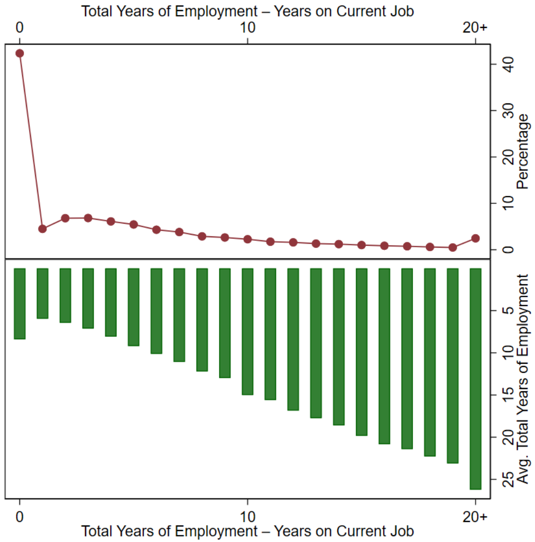
Sample Representativeness: Resales

Back



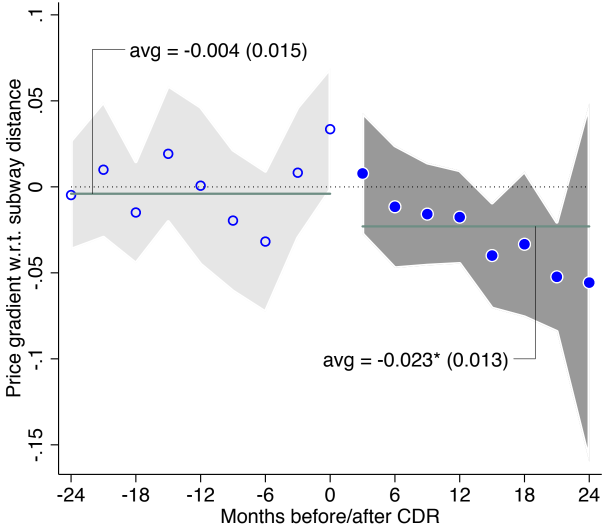
Job Tenure

▸ Back

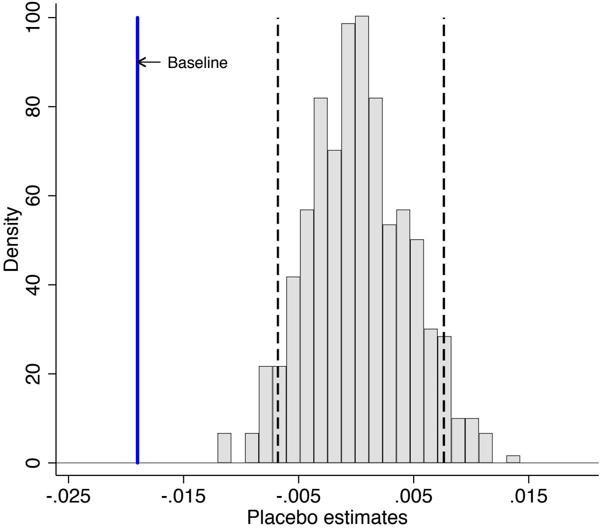


Event Study of Price Gradient Estimates

Table Back



Falsification Test on Price Gradient



Effect of Driving Restriction on Price Gradient

Back

	(1)	(2)	(3)	(4)
ln(Subway Distance)	-0.111***	-0.005	-0.004	0.003
	(0.015)	(0.016)	(0.015)	(0.018)
ln(Subway Distance) × CDR	-0.002	-0.018*	-0.019**	-0.033**
	(0.013)	(0.009)	(0.009)	(0.016)
Year-month FE	Y	Y	Y	Y
Neigborhood FE	N	Y	Y	Y
Complex-level Controls	N	N	Y	Y
Weighted	N	N	N	Y
Observations	9640	9634	9634	9634
Adjusted R^2	0.236	0.522	0.534	0.621

Note: Sample spans 24 months before and after CDR. The dep. var. is log(price/m^2).
* $p < 0.10$, **$p < 0.05$, *** $p < 0.01$

Sorting Near Subways and Jobs

Back

	ln(Distance to Subway) (1)	ln(Distance to Jobs) (2)
Ln(HH Income)	0.026	0.227***
	(0.020)	(0.048)
Ln(HH Income)$\times$ CDR	-0.041*	-0.109**
	(0.023)	(0.042)
Year-month FE	Y	Y
Neighborhood FE	Y	Y
Complex-level Controls	Y	Y
Household Demographics	Y	Y
Adjusted R^2	0.837	0.254

Note: Sample spans 24 months before and after CDR, 9634 observations. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

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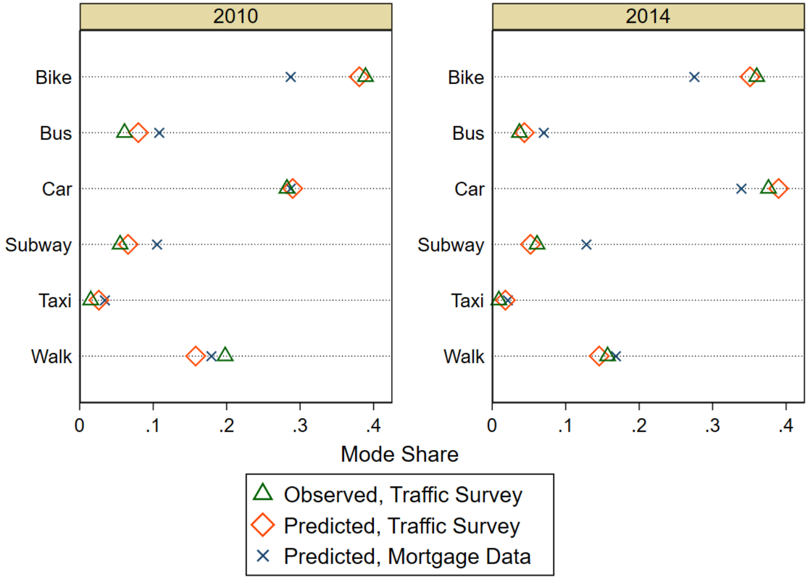
Model Fit: Travel Modes

Back



Density-Speed Function (Dep. var.: ln(speed))

Back

	(1)	(2)	(3)	(4)	(5)	(6)
ln(Density)	0.032	-0.173***	-0.683***	-1.018***	-1.099***	-0.620***
	(0.026)	(0.037)	(0.076)	(0.066)	(0.089)	(0.030)
Density Quintile	1	2	3	4	5	All
Density (cars/lane-km)	< 8	≥ 8 & < 14	≥ 14 & < 23	≥ 23 & < 35	≥ 35	All
Average speed (km/h)	65.3	70.9	63.8	50.0	30.3	60.5
Observations	393,634	386,717	412,556	243,302	156,670	1,592,879

Note: Each column reports results from a 2SLS regression where the dependent variable is ln(speed in km/h) and the key explanatory variable is log(traffic density in the number of cars/lane-km). The unit of observation is road segment by hour during peak hours within 6th ring roads in 2014. The IVs are constructed based on the driving restriction policy which has a preset rotation schedule for restricting certain vehicles from driving one day per week based on the last digit of the license plate number.

Within Household: Distance to Work vs. Income

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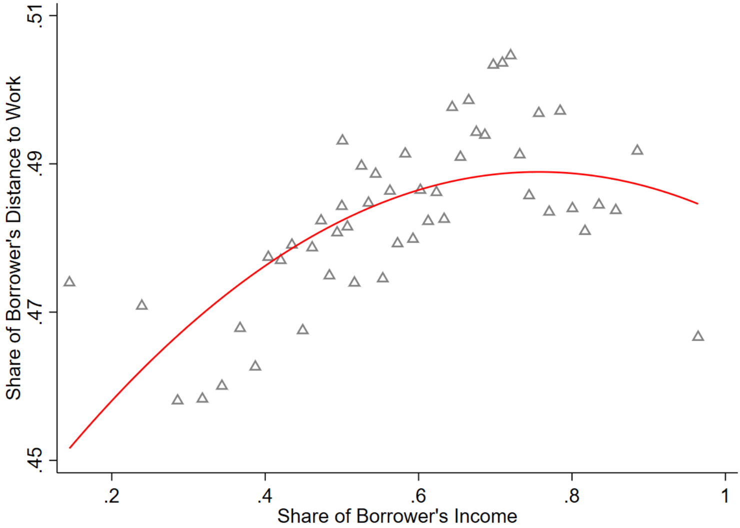

Note: Binned scatter plot showing that borrower's relative income share has weak relationship to borrower's share of distance to work.

Simulations: 2008 Network w/o Sorting

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	(1) No Policy Baseline levels		(2) Driving restriction Δs from (1)		(3) Congestion pricing Δs from (1)	
	High	Low	High	Low	High	Low
Panel A: travel outcomes						
Drive	45.01	25.62	-7.67	-3.48	-3.86	-5.23
Subway	7.51	9.28	1.24	0.43	0.40	0.75
Bus	5.20	10.08	0.42	-0.07	0.59	1.02
Bike	22.59	34.14	0.79	0.79	0.59	1.23
Taxi	3.22	1.76	2.89	1.52	1.29	1.15
Walk	16.48	19.13	2.34	0.81	0.99	1.09
Speed	22.87		4.32		4.08	
Panel B: housing market outcomes						
Distance to work (km)	19.45	18.88	0.00	0.00	0.00	0.00
Distance to subway (km)	6.94	7.62	0.00	0.00	0.00	0.00
Panel C: welfare analysis per household (thousand ¥)						
Consumer surplus			-175.1	-44.3	-164.1	-149.3
Toll revenue					222.3	222.3
Net welfare			-175.1	-44.3	58.2	73.1

Price Gradient under 2008 and 2014 Networks

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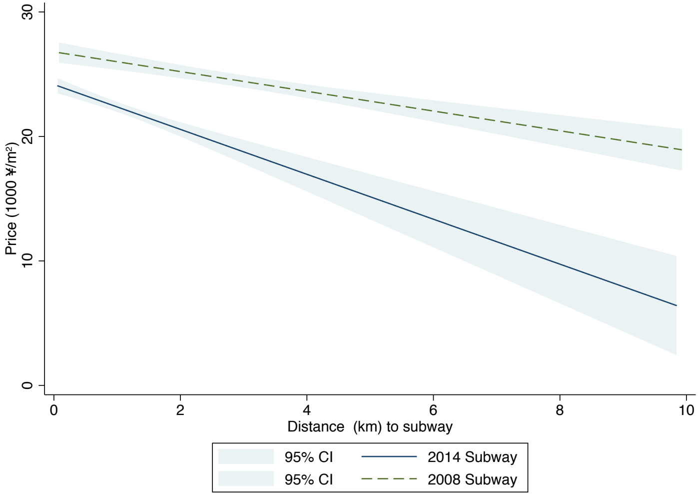
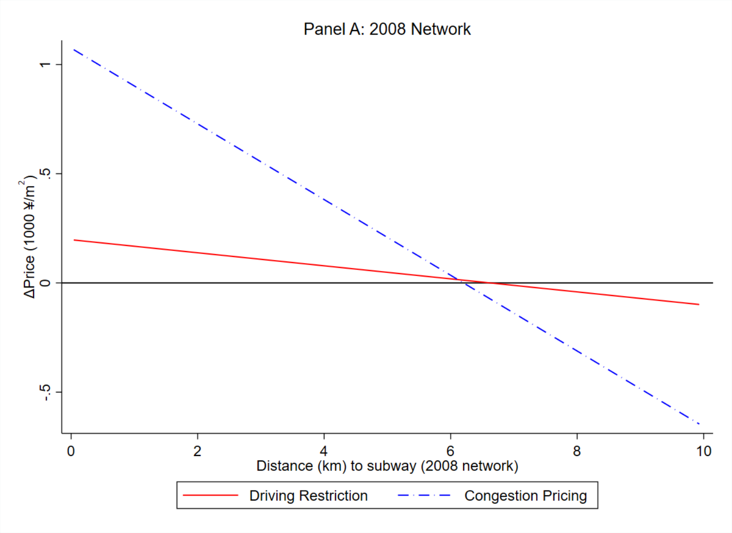


Change in Price Gradient Relative to the Baseline

▸ Back



Change in Price Gradient Relative to the Baseline

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